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Competing Mechanisms of the $0\nu\beta\beta$-Decay Mediated by Light Neutrinos within Left-Right Symmetric Models

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Abstract. We study light neutrino exchange mechanisms of the neutrinoless double beta decay in left-right symmetric seesaw models with right-handed gauge bosons at TeV scale. By assuming normal hierarchy of neutrino masses a qualitative comparison of involved total lepton number violating parameters is performed. We show that by using current constraint on the mass of heavy vector boson and its mixing with the light vector boson the dominance of the conventional light neutrino Majorana neutrino mass mechanism is expected.

1 Introduction

One of the most important open questions in neutrino physics is the question of whether neutrinos are Majorana or Dirac particles. Attempts to detect the (possible) Majorana nature of neutrinos focus around the neutrinoless double beta decay process ($0\nu\beta\beta$-decay):

$$(A, Z) \rightarrow (A, Z+2) + 2e^-. \tag{1}$$

If the $0\nu\beta\beta$-decay was observed, it would not only prove that neutrinos are Majorana particles, but it would also provide a measurement of the neutrino mass, if the conventional light neutrino exchange mechanism generated by left-handed V-A weak currents is the dominant mechanism of this process. In this case the inverse half-life of the $0\nu\beta\beta$-decay takes the form [1]

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu}(Q,Z) g_A^4 \left|M^{0\nu}\right|^2 \frac{\left|m_{\beta\beta}\right|^2}{m_e^2}, \tag{2}$$

where $G^{0\nu}(Q,Z)$, g_A and $M^{0\nu}$ are the phase-space factor, the axial-vector coupling constant and the nuclear matrix element of the process, respectively. The effective Majorana neutrino mass is given by

$$m_{\beta\beta} = \sum_i U_{ei}^2 m_i \; . \tag{3}$$

Here, U_{ei} and m_i (i=1,2,3) are elements of Pontecorvo-Maki-Nakagawa-Sakata neutrino mixing matrix and masses of neutrinos, respectively.

The left-right symmetric theories [2,3] provide a natural framework to understand the origin of neutrino Majorana masses. In such a scenario, there are additional contributions to the $0\nu\beta\beta$-decay from both left-handed and right-handed currents via exchange of light and heavy neutrinos, respectively. It is assumed that corresponding vector bosons W_L and W_R are a mixture of light and heavy vector bosons W_1 and W_2 and that mass of heavy vector boson might be around TeV – accessible at Large Hadron Collider.

In this contribution we pay attention to light neutrino exchange mechanisms of the $0\nu\beta\beta$-decay. We shall discuss whether W_L-W_R exchange mechanism (λ mechanism) or W_L-W_R mixing mechanism (η mechanism) might be the dominant mechanism of the $0\nu\beta\beta$-decay.

2 The $0\nu\beta\beta$-Decay Rate in the Case of Light Neutrino Exchange

We revisit light neutrino exchange contributions to the $0\nu\beta\beta$-decay in a TeV-scale left-right symmetric model for type-I seesaw dominance [2, 3].

The relation between left and right-handed vectors bosons (W_L and W_R) and mass eigenstates vector bosons (W_1 and W_2 with masses M_1 and M_2, respectively, where $M_1 < M_2$) is given by

$$\begin{pmatrix} W_L^- \\ W_R^- \end{pmatrix} = \begin{pmatrix} \cos\zeta & \sin\zeta \\ -\sin\zeta & \cos\zeta \end{pmatrix} \begin{pmatrix} W_1^- \\ W_2^- \end{pmatrix} . \tag{4}$$

The effective current-current interaction which can trigger the $0\nu\beta\beta$-decay can be written as [5]

$$H^\beta = \frac{G_\beta}{\sqrt{2}} \left[j_L^\rho J_{L\rho}^\dagger + \chi j_L^\rho J_{R\rho}^\dagger \eta j_R^\rho J_{L\rho}^\dagger + \lambda j_R^\rho J_{R\rho}^\dagger + h.c. \right] . \tag{5}$$

Here, $G_\beta = G_F \cos\theta_C$, where G_F and θ_C are Fermi constant and Cabbibo angle, respectively and $j_L(j_R)$ and $J_L(J_R)$ are the left-(right-) handed leptonic and hadronic currents, respectively. The coupling constants λ, η and χ are assumed to be real. We have

$$\begin{aligned} &\eta \simeq -\tan\zeta, \quad \chi = \eta, \\ &\lambda \simeq (M_{W_1}/M_{W_2})^2. \end{aligned} \tag{6}$$

The left-handed ν_{eL} and right-handed ν_{eR} electron neutrino eigenstates, which enter, respectively, in the j_L and j_R, are a superposition of the light and heavy mass eigenstate Majorana neutrinos ν_j and N_j,

$$\begin{aligned} \nu_{eL} &= \sum_{j=1}^{3} \left(U_{ej}\nu_{jL} + S_{ej}(N_{jR})^C \right), \\ \nu_{eR} &= \sum_{j=1}^{3} \left(T^*_{ej}(\nu_{jL})^C + V^*_{ej}N_{jR} \right). \end{aligned} \tag{7}$$

The 3×3 matrices U, S, T, V represent the generalizations of the Pontecorvo-Maki-Nakagawa-Sakata matrix. They constitute the 6×6 unitary neutrino mixing matrix [7]

$$\mathcal{U} = \begin{pmatrix} U & S \\ T & V \end{pmatrix}, \tag{8}$$

which diagonalizes the general 6×6 neutrino mass matrix:

$$\mathcal{M} = \begin{pmatrix} M_L & M_D \\ M_D^T & M_R \end{pmatrix}. \tag{9}$$

Here, M_L, M_R and M_D are, respectively, Majorana and Dirac mass submatrices. The full parametrization of matrix $\mathcal{U}$ includes 15 rotational angles and 10 Dirac and 5 Majorana CP violating phases. According to the [7] we can rewrite U as

$$\mathcal{U} = \begin{pmatrix} \mathbf{1} & \mathbf{0} \\ \mathbf{0} & U_0 \end{pmatrix} \begin{pmatrix} A & R \\ S & B \end{pmatrix} \begin{pmatrix} V_0 & \mathbf{0} \\ \mathbf{0} & \mathbf{1} \end{pmatrix}, \tag{10}$$

where $\mathbf{0}$ and $\mathbf{1}$ are the 3×3 zero and identity matrices, respectively. In the limit case A = $\mathbf{1}$, B =$\mathbf{1}$, R = $\mathbf{0}$ and S = $\mathbf{0}$ there would be a separate mixing of heavy and light neutrinos, which would participate only in left and right-handed currents, respectively. In that case only the neutrino mass mechanism of the $0\nu\beta\beta$-decay would be allowed and exchange neutrino momentum dependent λ and η mechanisms would be forbidden. If masses of heavy neutrinos are above the TeV scale, the mixing angles responsible for mixing of light and heavy neutrinos are small. By neglecting the mixing between different generations of light and heavy neutrinos A, B, R and S matrices can be approximated as follows:

$$A \approx \mathbf{1}, \quad B \approx \mathbf{1}, \quad R \approx \frac{m_D}{m_{LNV}}\mathbf{1}, \quad S \approx -\frac{m_D}{m_{LNV}}\mathbf{1}. \tag{11}$$

Here, the Dirac mass m_D represents energy scale of charge leptons and m_{LNV} is the total lepton number violating scale, which corresponds to masses of heavy neutrinos. Since V_0 is unknown, it is common to assume that the structure of V_0 is the same one as $U_0 = V_0 \equiv U$.

The $0\nu\beta\beta$-decay with the inclusion of right-handed leptonic and hadronic currents has been recalculated by considering exact Dirac wave function with finite nuclear size and electron screening of emitted electrons and the induced pseudoscalar term of hadron current, resulting in additional nuclear matrix elements [6]. By considering only the exchange of light neutrinos, for the $0\nu\beta\beta$-decay half-life we obtain

$$\frac{1}{T^{0\nu}_{1/2}} = g_A^4 |M_{GT}|^2 \Big\{ C_{mm} \frac{|m_{\beta\beta}|^2}{m_e^2} + C_{m\lambda} \frac{|m_{\beta\beta}|}{m_e} \langle\lambda\rangle \cos\psi_1 + C_{\lambda\lambda} \langle\lambda\rangle^2 + C_{m\eta} \frac{|m_{\beta\beta}|}{m_e} \langle\eta\rangle \cos\psi_2 + C_{\eta\eta}\langle\eta\rangle^2 + C_{\lambda\eta}\langle\lambda\rangle\langle\eta\rangle \cos(\psi_1 - \psi_2) \Big\}. \quad (12)$$

The effective lepton number violating parameters and their relative phases are given by

$$\begin{aligned} |m_{\beta\beta}| &= |\sum_{j=1}^{3} U_{ej}^2 m_j|, \\ \langle\lambda\rangle &= \lambda |\sum_{j=1}^{3} U_{ej} T_{ej}^* (g_V'/g_V)|, \\ \langle\eta\rangle &= \eta |\sum_{j=1}^{3} U_{ej} T_{ej}^*|, \\ \psi_1 &= \arg\Big[\sum_{i,j=1}^{3} (m_i U_{ei}^2)(U_{ej} T_{ej}^* \frac{g_V'}{g_V})^*\Big], \\ \psi_2 &= \arg\Big[\sum_{i,j=1}^{3} (m_j U_{ej}^2)(U_{ej} T_{ej}^*)^*\Big]. \end{aligned} \quad (13)$$

The coefficients C_I (I = mm, $m\lambda$, $m\eta$, $\lambda\lambda$, $\eta\eta$ and $\lambda\eta$) are combinations of products of nuclear matrix elements and phase-space factors:

$$\begin{aligned} C_{mm} &= (1-\chi_F+\chi_T)^2 G_{01}, \\ C_{m\lambda} &= (\chi_F-\chi_T-1)\left[\chi_{2-}G_{03} - \chi_{1+}G_{04}\right], \\ C_{m\eta} &= (1-\chi_F+\chi_T)\left[\chi_{2+}G_{03} - \chi_{1-}G_{04} - \chi_P G_{05} + \chi_R G_{06}\right], \\ C_{\lambda\lambda} &= \chi_{2-}^2 G_{02} + \frac{1}{9}\chi_{1+}^2 G_{011} - \frac{2}{9}\chi_{1+}\chi_{2-}G_{010}, \\ C_{\eta\eta} &= \chi_{2+}^2 G_{02} + \frac{1}{9}\chi_{1-}^2 G_{011} - \frac{2}{9}\chi_{1-}\chi_{2+}G_{010} \\ &\quad + \chi_P^2 G_{08} - \chi_P\chi_R G_{07} + \chi_R^2 G_{09}, \\ C_{\lambda\eta} &= 2\Big[\frac{1}{9}\left(\chi_{1+}\chi_{2+} + \chi_{2-}\chi_{1-}\right)G_{010} - \chi_{2-}\chi_{2+}G_{02} - \frac{1}{9}\chi_{1+}\chi_{1-}G_{011}\Big]. \end{aligned} \quad (14)$$

The explicit form of phase-space factors G_{0k}, matrix element M_{GT} and ratios of matrix elements χ_I is given in [6].

3 Study of Importance of Different $0\nu\beta\beta$-Decay Mechanisms

The $0\nu\beta\beta$-decay half-life in Eq. (12) includes three effective total lepton number violating parameters $\eta_\nu \equiv m_{\beta\beta}/m_e$, $\langle\lambda\rangle$ and $\langle\eta\rangle$. The importance of particular $0\nu\beta\beta$-decay mechanism associated with them depends also on values of C_{mm}, $C_{m\lambda}$, $C_{m\eta}$, $C_{\lambda\lambda}$, $C_{\eta\eta}$ and $C_{\lambda\eta}$ coefficients, which are a superposition of products of different nuclear matrix elements and phase-space factors G_{0k} ($k = 1, \ldots, 11$). In [6] (see TABLE VI) it was shown that if $|\langle\lambda\rangle/\eta_\nu| \approx 1$ ($|\langle\eta\rangle/\eta_\nu| \approx 10^{-2}$) the λ (η) mechanism is of comparable importance with the $m_{\beta\beta}$ mechanism. In the case this ratio is smaller than unity (10^{-2}) there is a dominance of light neutrino mass mechanism over the λ (η) mechanism of the $0\nu\beta\beta$-decay.

By taking advantage of Eq. (11) for the effective lepton number violating parameters associated with right-handed currents we obtain [6]

$$\begin{aligned} \langle\lambda\rangle &\approx (M_{W_1}/M_{W_2})^2 \frac{m_D}{m_{LNV}} |\xi| \,, \\ \langle\eta\rangle &\approx -\tan\zeta \frac{m_D}{m_{LNV}} |\xi| \,, \end{aligned} \tag{15}$$

with

$$\begin{aligned} |\xi| =& |c_{23}c_{12}^2c_{13}s_{13}^2 - c_{12}^3c_{13}^3 - c_{13}c_{23}c_{12}^2s_{13}^2 - c_{12}c_{13}\left(c_{13}^2s_{12}^2 + s_{13}^2\right)| \\ &\simeq 0.82. \end{aligned} \tag{16}$$

Here, $c_{ij} \equiv \cos(\theta_{ij})$ and $s_{ij} \equiv \sin(\theta_{ij})$ with mixing angles θ_{12}, θ_{13} and θ_{23} entering to the PMNS matrix. In a similar way $m_{\beta\beta}$ can be expressed in terms of the Dirac mass m_D and parameter m_{LNV} as follows:

$$\eta_\nu = \frac{m_{\beta\beta}}{m_e} = \sum_i U_{ei}^2 \frac{m_i}{m_e} = \frac{m_D}{m_{LNV}} \frac{m_D}{m_e} \sum_i U_{ei}^2 \frac{m_i m_{LNV}}{m_D^2} \approx \frac{m_D^2}{m_{LNV} m_e}. \tag{17}$$

Here, it is assumed $\sum_i U_{ei}^2 \frac{m_i m_{LNV}}{m_D^2} \approx 1$, i.e., there is no anomaly cancellation among terms, which constitute $m_{\beta\beta}$.

Within the assumed approximations by evaluation of effective lepton number violating parameters we get

$$\left|\frac{\langle\lambda\rangle}{\eta_\nu}\right| = \left(\frac{M_{W_1}}{M_{W_2}}\right)^2 \frac{|\xi| m_e}{m_D}, \qquad \left|\frac{\langle\eta\rangle}{\eta_\nu}\right| = \tan\zeta \frac{|\xi| m_e}{m_D} \,. \tag{18}$$

The above ratios depend on parameters associated with the seesaw mechanism (m_D and m_{LNV}) and right-handed currents (ζ and M_2). It is naturally to assume 1 MeV $\leq m_D \leq$ 1 GeV, i.e., the Dirac neutrino mass fits approximately to all charged fermion masses, and $m_{LNV} \geq$ TeV. From collider experiments current constraint on the mixing angle of the left and right vector bosons is $\zeta < 0.013$ and lower bound on the mass of the heavy vector boson is $M_2 > 2.9$ TeV [8].

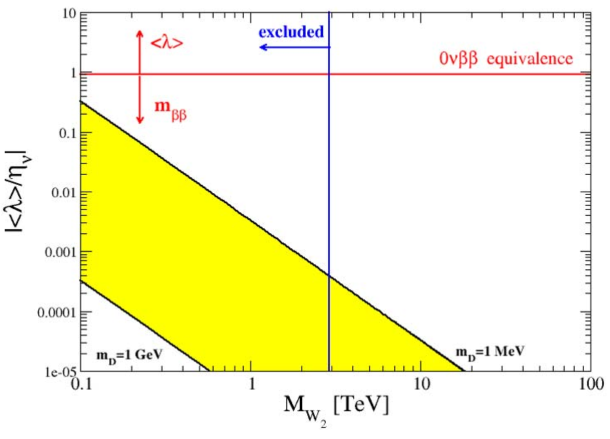

Figure 1. The ratio $|\langle\lambda\rangle/\eta_\nu|$ as a function of the mass of the heavy vector boson W_2. The line of the $0\nu\beta\beta$ equivalence ($|\langle\lambda\rangle/\eta_\nu| \approx 1$) corresponds to the case of equal importance of both $m_{\beta\beta}$ and λ mechanisms in the $0\nu\beta\beta$-decay.

In Figures 1 and 2 $|\langle\lambda\rangle/\eta_\nu|$ and $|\langle\eta\rangle/\eta_\nu|$ are plotted as function of M_2 and $\tan\zeta$, respectively. For the Dirac mass we assume 1 MeV $< m_D < 1$ GeV. By using the present limit on M_2 we see that the λ mechanism is excluded as the dominant mechanism of the $0\nu\beta\beta$-decay. If more stringent limit on ζ parameter will be determined in future, the dominance of the η mechanism will be excluded as well.

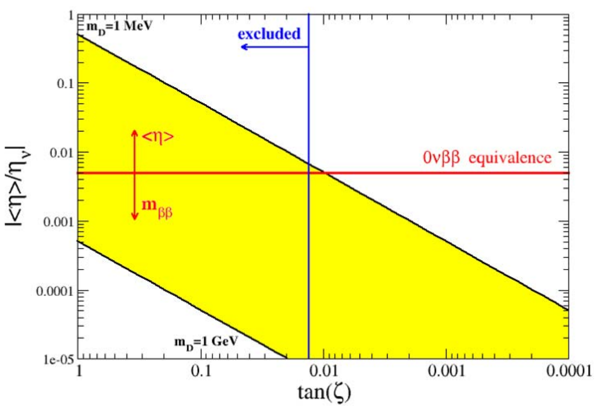

Figure 2. The ratio $|\langle\eta\rangle/\eta_\nu|$ as a function of the $\tan\zeta$. The line of the $0\nu\beta\beta$ equivalence ($|\langle\lambda\rangle/\eta_\nu| \approx 10^{-2}$) corresponds to the case of equal importance of both $m_{\beta\beta}$ and η mechanisms in the $0\nu\beta\beta$-decay.

4 Conclusions

In summary, the left-right symmetric model scenario of the $0\nu\beta\beta$-decay was discussed by assuming the seesaw and the lepton number violation above the TeV scale. The question was addressed whether the momentum-dependent contributions to $0\nu\beta\beta$-decay involving final-state electrons with opposite helicities, i.e., the so-called λ and η contributions, could be significant. By making viable assumptions and using the current constraints on mass and mixing of heavy vector boson we conclude that the dominance of these mechanisms is practically excluded. Thus, there is a chance that the observation of the $0\nu\beta\beta$-decay will allow to determine the absolute neutrino mass scale of light neutrinos.

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